

PAPER

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Impact of strong repeated ground excitation to the on-plan rotation of asymmetric building with various strength and stiffness eccentricities

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Abstract. Buildings subjected to torsional effect may result to the floors of the building not only translate laterally but also rotate vertically. Torsional effects may significantly modify the seismic response of buildings, and even cause severe damage or collapse of structures. The current practices in earthquake design is to apply single earthquake on structure during modelling and analysis. However, in real earthquake occurrence, the earthquakes normally occurred repeatedly after the first event. This phenomenon can affect the stiffness and strength of the structural system especially for repeated strong motions. With greater damage expected and lack of time, any rehabilitation action is impractical. Slab rotation, a major response parameter to represent the severity of the torsional response of eccentric systems, is considered. The centre of strength (CR) and centre of stiffness (CS), as two interdependent and important factors to the torsional response of buildings, are investigated via eighty positions of strength eccentricities (e_r) and stiffness eccentricities (e_s). Hence, this paper presents the torsional behaviour of a single storey, three-dimensional asymmetric building under the excitation of single and repeated strong ground motions. These motions are applied in the z-direction and analysed for elastic and inelastic conditions. The results are interpreted based on two position models. Position Model A concludes that the effectiveness of CS reduces gradually until CS ratio (e_s/b_z) ≤ 0.2 ; thereafter effectiveness of CR increases to cause elastic slab rotation. With repeated ground motion, the magnitude of inelastic rotation is increased; however $e_s/b_z \leq 0.2$ is maintained showing effectiveness of stiffness eccentricity irrespective of nature of ground motion. Position Model B shows that slab rotation is affected by repeated ground motion. Elastic/inelastic analysis under repeated ground motion must be conducted in oppose to current practice, so that the designed structure can undertake the elastic/inelastic demand; especially for the lower CR ratio values.

1. Introduction

Buildings with non-uniform mass, stiffness and/or strength over their plan are often described as being torsionally irregular. Even for structures designed to be perfectly regular, the movement of live loads around the structure can cause torsional irregularity which in turn changes the member demands [2]. Torsional effects may significantly modify the seismic response of buildings, and they have caused severe damage or collapse of structures in past earthquakes. These effects occur due to different reasons, such as no uniform distribution of the mass, stiffness and strength, torsional components of the ground movement, etc. Hence due to the torsional effects, the floors of the building not only translate laterally but also rotate along a vertical axis. In ductile structures, the main consequence of floor twist is an unequal demand of lateral displacements in the elements of the structure [1].

Design codes incorporate special requirements to take into account the torsional effects, which usually imply de amplification of eccentricity and the consideration of an accidental eccentricity. These requirements are mainly based on elastic considerations developed several decades ago. These criterion considers the torsional effect induced by the earthquake can be represented in the static analysis of building. When dynamic analysis is performed, only the accidental eccentricity is considered [1]. Most building codes, as listed in IAEE 2000, over years, recommend equivalent static



analysis to account for torsion. Concept of design eccentricity is suggested to account for seismic torsion owing to asymmetry [4]. Another aspect of the code accidental eccentricity provisions to be considered is the fact that they were introduced on the basis of elastic investigations carried out using often oversimplified building models. Subsequent application of this concept to realistic buildings responding in the inelastic range under design level earthquakes has been made rather intuitively and without the necessary supporting volume of research [15].

Strength eccentricities (CR) and stiffness eccentricities (CS) are two interdependent and important parameters in the code provision for torsion design in building. Design eccentricity related to locations of CR and CS continues to be practiced as a basic approach for design of asymmetric structures over years. Investigations on how to apply such provisions in real structures also attract the interest of the researchers [4]. Among studies are done are by Tso and Myslimaj [6] where the CS is located at opposite side of CR with the same eccentricity or also called as a balanced CS-CR location. This criterion is used to minimize the torsion of asymmetric building. While DeStefano and Pintucchi [7] considers to put the CS and CR at the same side by using a one-story model taking into account that the total strength to be distributed proportionally among the vertical resisting elements. To represent the real buildings, the CS has been put halfway between the CR and the CM to account for torsional effects unavoidably results in a more balanced strength distribution. Significant parametric works have been done to quantify and/or predict the effect of torsional irregularity by considering CS and CR; however, these are largely using 2-D analyses [2,8,18,19].

An example of severe damage occurred during the Michoacán Earthquake, Mexico, 1985 shows the importance of torsional effects and the need to improve the design requirements. Detailed analysis of the severe damage revealed that about “50% of the failures were either directly or indirectly attributable to asymmetry of structural form, stiffness/strength or mass distributions [7]. Several other destructive earthquakes that occurred in 1994 Northridge, CA; 1995 Kobe, Japan; 1999 Chi Chi, Taiwan, and 2001 Bhuj, India [8] confirmed the greater vulnerability of irregular structures. A number of buildings around the Central Business District are reported to suffer from significant torsional damage during the Christchurch earthquake in 2011. The 2016 Kumamoto, Japan earthquake is another recent example that re-affirms the deficiency of the existing guidelines for the design of irregular structures [4]. The current practices in earthquake engineering such as FEMA 368 and the Eurocode 8 only apply single earthquake on building structure during modelling and analysis while the effects of the repeated earthquake phenomena is ignored. However, in real earthquake event, the earthquake always occurred repeatedly after the first one [13,17]. This repeated phenomenon can affect the stiffness and strength degradation of the structural system especially for repeated strong ground motions. Loulelis et al [11] who examines the seismic behaviour of plane moment resisting steel frames (MRF) to repeated strong ground motions mentions that a sequence of earthquakes results in a significant damage accumulation in a structure. This is because any rehabilitation action between two successive seismic motions cannot be done due to lack of time

Design of asymmetric building is often conducted using 2-D analysis resulting torsional effects and inelastic behavior are not considered explicitly [2,4,15]. Elastic models were used in earlier works but were gradually replaced by inelastic models, since building response under design level earthquakes is expected to be inelastic [15]. However, code provisions till today have been based mostly on results from one-story inelastic models or on results from elastic multi-story idealizations. Concerns arises about inelastic response of buildings based on one-story simplified model by Anagnostopoulos *et al* [15]. Anagnostopoulos et.al [10,15] highlighted the concerns of using one story inelastic shear beam models suggesting results obtained are strictly for the models themselves. In practicality, past researches with one-story model selected more or less arbitrarily the element stiffness and the corresponding element strengths were determined based only on the earthquake action. Mass and mass moment of inertia were then set to produce systems with the desired frequency and Ω ratios. Among the concerns include (a) The stiffness and strength of the resisting elements of the one-story model are usually specified and calculated independent of each other and only for seismic loads (b) A number of loading conditions and limitations used for design in real buildings are typically not considered with

simplified models, whose strength and stiffness is almost always determined from the seismic loading alone. (c) Yielding of an end-element of the simplified model implies the practical elimination of the stiffness in that position (only the post-yield stiffness is left). (d) complex vibrational patterns of multistorey buildings cannot be reproduced because higher mode effects are totally ignored by the one-story models (e) In order to have at least qualitative agreement between results from one-story and multi-story models, key properties of the two models must be matched. These concerns have been overlooked in most cases and unjustified generalizations and conclusions are often made.

Hence, this paper presents a study to full fill a research gap on the torsional behaviour due to CR and CS influence subjected to repeated strong ground motion. A single storey, three-dimensional asymmetric building which attempts to represent the real building behaviour based on the shortcomings presented by Anagnostopoulos et.al [10][15] is adopted. Single and repeated strong ground motions are applied in the z-direction. An inelastic dynamic time history analyses is done based on elastic and inelastic conditions. Slab rotation effect is considered as a response parameter to represent the severity of the torsional response of eccentric systems.

2. The structural model

A simple model that is attempted represent the real building to address the shortcomings presented by Anagnostopoulos et.al [10,15] are adopted in this study. The model has been used in an ongoing research [9,22] and been verified using push-over analysis. It is an attempt to resemble a real building [15] where the properties of the perimeter walls, W1 and W4 are interrelated; whereby if one changes, the other change too. Concurrently, although the element stiffness and strength were determined based on earthquake action, checks are made on capacity from design due gravity loads and several other criteria, such as interstory drift limitations, capacity design provisions, and minimum section and stability requirements are within EC8 code requirement. The higher mode effects are negligible since the building is a low rise structure. The building model used is a single-storey, asymmetric 3-D building with a rigid floor diaphragm supported by four shear walls as shown in Fig. 1(a). The walls are located at the perimeter of the building to provide lateral force resistance. The floor diaphragm concentrates the entire story mass at the Centre of Mass (CoM). The building is supported on fixed supports; neglecting soil-structure interaction. The model's width, b_z , is taken as 26m and breadth, L , as 15m. The dimensions of the model are based on Stefano and Pintucchi [7] where the non-dimensionalized mass radius, ρ , is taken as 0.33, which is a value typical of many real buildings with plan aspect ratio $B/L=0.577$. The terms for CoM, CR, CS, er and es shown in Fig.1(b) denote the Center of Mass, Center of Strength, Center of Stiffness, strength eccentricity and stiffness eccentricity, respectively. The CR and CS are located along the x-axis at a given distance from CoM where er and es representing CR's and CS's respective distances from CoM. Fig. 1(b) also shows the on-plan view of the four shear walls, W1, W2, W3 and W4 for the model in the present study. Their dimensions are indicated in Table 1; where W1, W2 and W3 have fixed b (breadth) x h (width) while for E1, b is fixed with varying h value. The dimensions of h are obtained by varying the CR coefficient as shown in Table 3. The h values that are used is shown in Table 2. At the same time, the fundamental period of vibrations, T_i is kept constant.

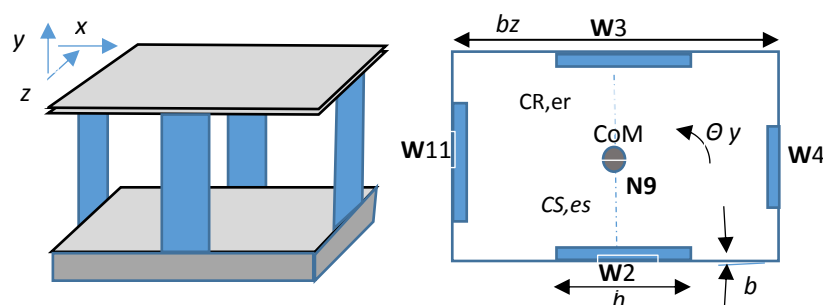


Figure 1.(a) Simple 3-D building model (b) on-plan view of shear wall elements

Table 1 Dimension of Wall elements

Wall Element	b (m)	h (m)
W1	0.5	varies
W2	3.5	0.5
W3	3.5	0.5
W4	0.5	2

Table 2. h values based on CR condition

Position	CR	h (m)
1	0.05L	2.15
2	0.1L	2.32
3	0.15L	2.5
4	0.2L	2.71
5	0.25L	2.95
6	0.3L	3.24
7	0.35L	3.67
8	0.4L	4.29

The model is mass eccentric where the CoM, coincides with the Geometric Center, GC. To simplify the analysis, a master node, node 9, located at the CoM of the floor and all nodes at the same floor are constrained to node 9 so that the maximum rotation about y-axis, θ_y , for the whole floor exhibited the same magnitude. The maximum rotation is the rotation that occurred over the whole course of the earthquake. Seven ground motions are applied in z-direction under elastic and inelastic conditions. The results of the analyses are in terms of mean values (averaged over the considered input ground motions) of the elastic and inelastic maximum rotation at node 9. Averaged values have been used in other studies [8,14]. The reason to such averaging of values is to make conclusions on rotation value less dependent on the characteristics of specific motions [15]. The nonlinear time-history analyses of the 3D model are carried out using the structural analysis program "Ruaumoko3D" a software also used by Castillo [19], Beyer [8] for similar parametric studies of 2D systems. The analyses were performed with tangent-stiffness proportional Rayleigh damping with 5% damping for the second mode.

3. Strength and stiffness eccentricities

The CS and CR coefficients designed in this study is to emphasize the strength and stiffness interdependence of shear wall elements W1 and W4. Their strength and stiffness calculations are based on the ratios in Table 3. The five coefficients designed include the criteria proposed by Tso and Myslimaj [6] as well as Stefano and Pintucchi [7]. The coefficients of CR are also based on the real building coefficient as proposed by Anagnostopoulos [10]. The varying CR and CS are applied by varying strength eccentricities (e_r) and stiffness eccentricities (e_s) respectively, along the x-axis from the CoM (where L is the slab width). Positive CR/CS value refers to the ' e_r ' and ' e_s ' on the same side of each other, from the CoM (ie. left side of CoM). The more positive the CR coefficient, the ' e_r ' is closer to wall W1 leading to the increment of the wall strength for wall W1. When CS has negative coefficients, ' e_s ' is on the opposite side of ' e_r ' with CoM in between them, resulting to ' e_s ' closer to wall W4. The CoM is given a position of '0' on the graph's x-axis.

Table 3. Variations of strength and stiffness eccentricities

Models	CR	e_r (m) (from CoM)	CS/CR	e_s (m)
1	0.05 L	1.3	CS = -1.0 CR	Opposite side (right side of CoM)
2	0.1 L	2.6	CS = - 0.5CR	
3	0.15 L	3.9	CS = 0 CR	At CoM
4	0.2 L	5.2	CS= 0.5CR	Same side (left of CoM)
5	0.25 L	6.5	CS= 1.0 CR	

6	0.3 L	7.8
7	0.35 L	9.1
8	0.4 L	10.4

In order to study the effect of strength and stiffness on the structure, two position models are proposed. Due to space limitation, physical arrangement of CM, CR and CS for Model A and Model B can be obtained from an ongoing research, Azida [22] as summarized in Table 3. Position Model A is to highlight the significant importance of CR on slab rotation which consists of 40 CS/CR conditions derived from 8 constant CR versus 5 varying CS coefficients. These positions models serves as the distinctive gap which have not been used in other studies. Position Models B, proposed by Suhaila [9], is to highlight the significant importance of CS on slab rotation by considering 40 CS/CR conditions derived from 5 constant CS versus 8 varying CR coefficients. For example, subModels A1 CR=0.05 will have CR= (constant) =0.05 and 5 varying CS conditions namely CS = -1.0 CR, -0.5 CR, 0 CR, 0.5 CR and 1.0 CR. Meanwhile, subModels B1 CS= -1.0 will have CS= (constant) = -1.0 and 8 varying CR coefficients namely CR = 0.05L, 0.1L, 0.15L, 0.2L, 0.25L, 0.3L, 0.35L and 0.4L.

4. Seismic Input

In this study, a total of seven strong ground motions with magnitude in the range of 6.33 to 7.6 Mw classified as Near Fault ground motion with forward directivity effect are used based on published record by Baker [12]. For scaling purpose, the Type 1 response spectrum of EC 8, for condition of Soil B and Seismic Zone III at Greece have been used. The complete list of these earthquakes, which are downloaded from the strong motion database of the Pacific Earthquake Engineering Research (PEER) Center appears in Table 4. Every sequential ground motion record from the PEER database becomes a single ground motion record (serial array) by applying a time gap equal to 100 sec between two consecutive seismic events. This gap has zero acceleration ordinates and is completely adequate to cease the motion of any structure due to damping before the action of the next event [14]. Seven sets of repeated earthquake consisting of 2 motions each were generated with appropriate scale factor as proposed. Thus, the GM1 and GM2 represent the single and two repeated ground motions (with after-shock only) respectively as shown in Figure 2.

Table 4. Strong Ground Motion

No.	Date	Earthquake Name	Mag. (Mw)	Station	PGA (g)		Scale to RSA(T1)=1.08g	
					Major	Major	Major	Minor
1	1994	Northridge-01	6.69	“Jensen Filter Plt Admin Bldg”	0.9556	1.1302	0.3607	2.9945
2	1994	Northridge-01	6.69	“Jensen Filter Plant Generator Building”	0.9555	1.1303	0.3607	2.9942
3	1999	Chi-Chi_ Taiwan	7.62	“TCU052”	0.5161	2.0926	1.8327	0.5893
4	1980	Victoria_ Mexico	6.33	“Cerro Prieto”	0.8381	1.2886	1.5808	0.6832
5	1971	San Fernando	6.61	Pacoima Dam (upper left abut)	2.0011	0.540	0.573	1.8852
6	1992	Big Bear-01	6.46	“Snow Creek”	0.1458	7.4070	3.9820	0.2712
7	1978	Tabas_ Iran	7.35	Tabas	1.5618	0.692	0.591	1.8261

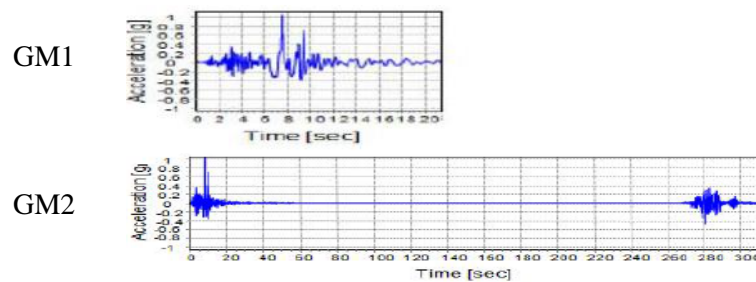


Figure 2. Typical profile of generated ground motion

5. Results and discussion

5.1 Model A: Constant Centre of Strength, CR

The trend of four graphs in Figure 3(a), (b), (c) and (d) for inelastic and elastic maximum rotation versus the normalized stiffness eccentricities ratio (e_s/bz) along the slab x-axis with 40 different CS/CR conditions shows increasing rotations with increasing CR. It is apparent from Figure 3(a)-(b) that all elastic rotations for single and repeated ground motions are constant i.e horizontal lines. However, Figure 3(b) shows the maximum elastic rotation for A8 CR=0.40L due to repeated ground motion GM2 increased by 60% as oppose to rotation due to single ground motion GM1. As seen in Fig. 3(c)-(d), inelastic rotations mostly occur when CR>0.2L away from both side of the Centre of Mass (CoM) at normalized $e_s/bz = 0.45$. Rotations still remain elastic when normalized $e_s/bz < 0.45$ at CR<0.2L because the system stiffness is still strong to overcome the applied rotation.

A possible explanation to this behaviour is as follows. Referring to Fig. 3(c)-(d) when CR=0.05L at normalized $e_s/bz < 0.2$, rotations remains elastic although the wall strength is weak because the influence of stiffness eccentricity, e_s , is effective. That is, the wall stiffness is strong to overcome the applied rotation. However, considering CR=0.05L at normalized $e_s/bz > 0.2$, the strength eccentricity, e_r , is closest to CoM and the longest perimeter wall in the z-direction, ie wall W1, has its least strength. In this condition, the wall strength is not strong to overcome the applied rotation; thus resulting inelastic rotation. This also indicate wall stiffness is no more effective. Generally, at higher range of CR>0.2L (i.e. the centre of strength move towards the longer wall), the wall W1 strength increases to overcome wall stiffness resulting to the rotations stabilize as elastic rotations. Thus, the wall strength is able to counter and control induce rotation due to the earthquake to produce elastic rotation. This situation is also obtained by Beyer [2009][8] whereby similar result at zero strength eccentricity ratio ie CR=0 at $e_s/bz = 0.17$ produced some displacement indicating stiffness eccentricity had some influence on displacement demand. Beyer [2009][8] also observed increase in wall strength when centre of strength moved towards the perimeter wall. Beyer [2009][8] also suggests that the influence of stiffness eccentricity is more prominent on the smaller displacement ductilities rather than for larger displacement ductilities.

Therefore, it can be concluded that the effectiveness of CS reduces gradually until stiffness eccentricity ratio (e_s/bz) of 0.2; thereafter effectiveness of CR increases. This condition agrees with the suggestion by Sommer [2000][18] that stiffness eccentricity plays a minor role when assessing the torsional behaviour of ductile systems. Surprisingly, with repeated ground motion, only the maximum inelastic rotation of the slab increased but elastic rotation at stiffness eccentricity ratio of 0.2 is maintained similar to that obtained due to GM1.

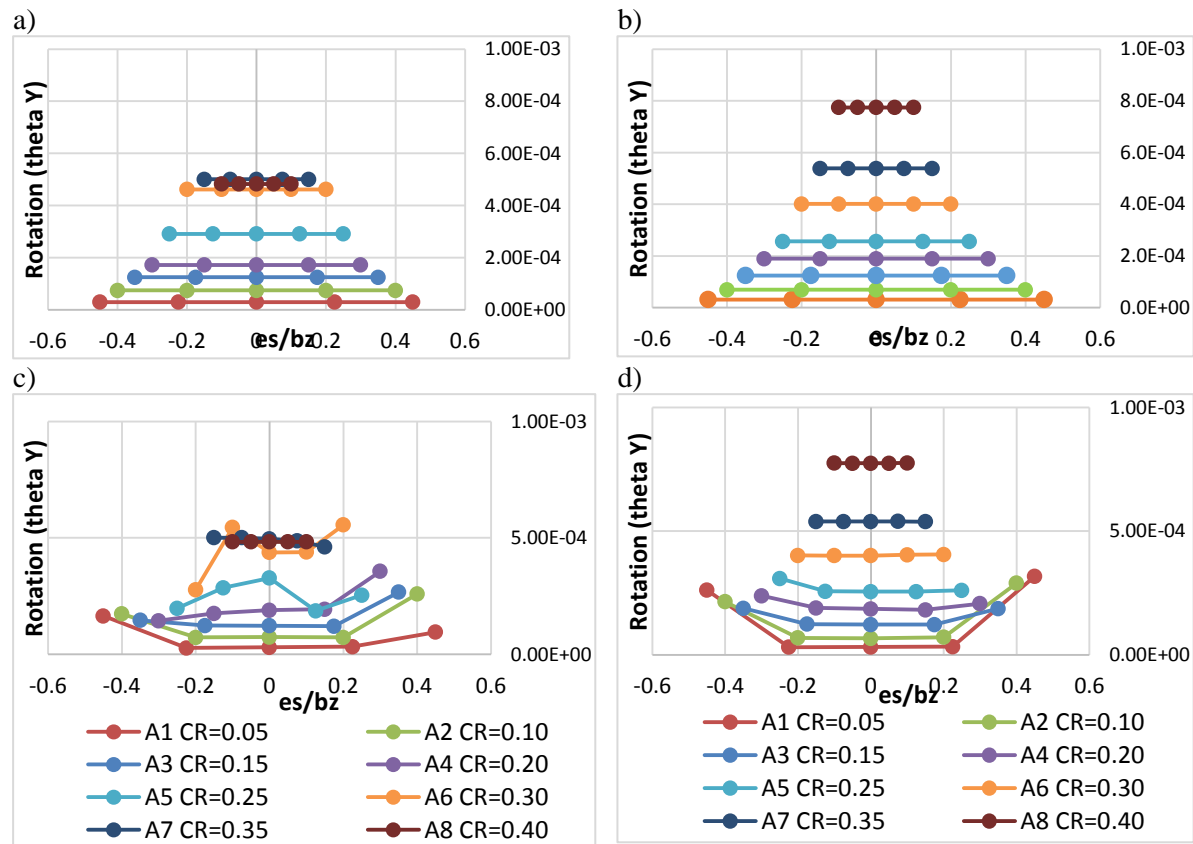


Figure 3. Model A Maximum Rotation versus vary CS for constant CR for single (GM1) and repeated (GM2) strong ground motion (a) GM1 elastic Rotation (b) GM2 Elastic rotation (c) GM1 Inelastic Rotation (b) GM2 Inelastic rotation

5.2 Model B Constant Centre of Stiffness, CS

All sub-models B produce one common graph of inelastic and elastic rotation implying that CS values has no or minimum effect on the rotation of the slab. Similarly, one common graph is also obtained due to repeated ground motion for all the sub-models B. Figure 4(a) shows the comparison between elastic and inelastic rotations for Model B due to strong single ground motion, GM1. The trend of rotation is similar to the trend obtained by Azida [22] but with a prominent difference in rotation demands between the elastic and inelastic rotation. For $er/bz \leq 0.17$, the maximum inelastic rotation is just about larger than the elastic system. This trend is also observed with Beyer's [8] work where rotation is inelastic for smaller strength eccentricities ratio (er/bz) < 0.14 and reaching elastic at higher er/bz ; as seen in Fig. 4(b). As discussed by Beyer (2009), when $CR \leq 0.14$, the maximum rotation is just about larger for the inelastic than for the elastic rotation probably related to the wall goes into the inelastic range. Figure 5(a) shows the overall variation of elastic and inelastic rotations increase in a parabolic trend for repeated strong ground motion, GM2. The graph of inelastic rotation is greater than elastic rotation at a strength eccentricities ratio (er/bz) < 0.3 which is two times greater than that due to GM1. Figure 5(b) presents the overall variations of elastic and inelastic rotations for single and repeated ground motions with respect to varying CR. All the elastic and inelastic rotations due to GM1 and GM2 increases with increasing CR where the maximum slab rotation for GM2 is about 55% higher than GM1. By comparing all the elastic and inelastic rotations from GM1 and GM2, it is found that the inelastic rotation of GM2 has a significant overall influence to maximum inelastic slab rotations for smaller $er/bz < 0.27$. Out of normal expectation, elastic rotation from GM1 gives the maximum rotation when the $0.27 < er/bz < 0.34$. At higher $er/bz > 0.34$, the maximum rotation is elastic rotation due to GM2. From this study, it is found that strong repeated ground motion gives

highest overall (elastic) rotations at high strength eccentricity but over the lower range of $e_r/b_z < 0.27$, the inelastic rotations due to repeated ground motion has become most prominent. It can be concluded that although structure under single strong ground motion can be sufficiently be designed in the elastic range as suggested by Summer [18], the findings from this work shows otherwise such that structural behaviour are affected by repeated ground motion. That is, inelastic analysis under repeated ground motion is must be conducted to ensure that the structure to be designed can undertake the expected elastic/inelastic demand from repeated ground motion; especially for the lower CR ratio values.

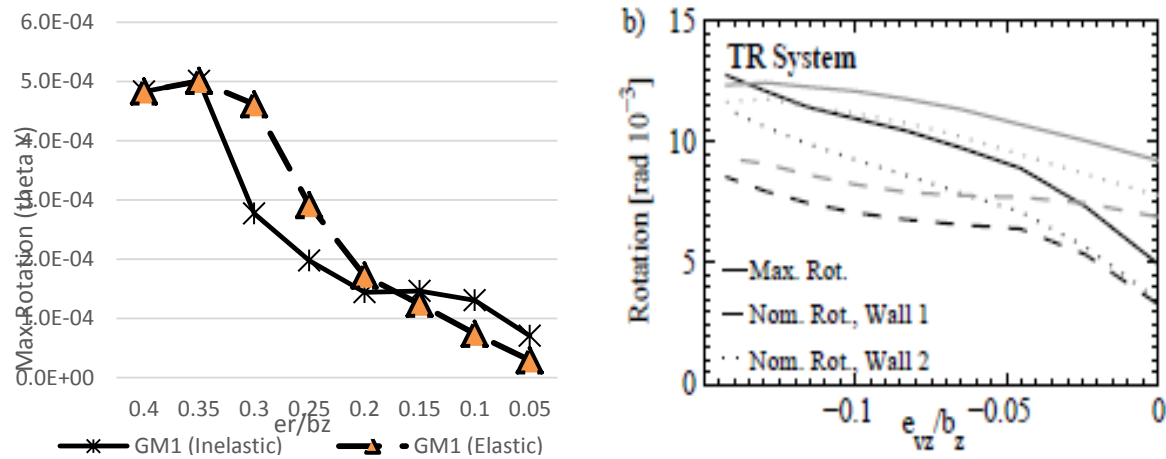


Figure 4 (a) Model B: Rotation demand for single strong ground motion (elastic and inelastic systems) versus e_r/b_z by 3D analysis (b) Beyer's [6] Rotation demand for elastic and inelastic systems by 2D analysis

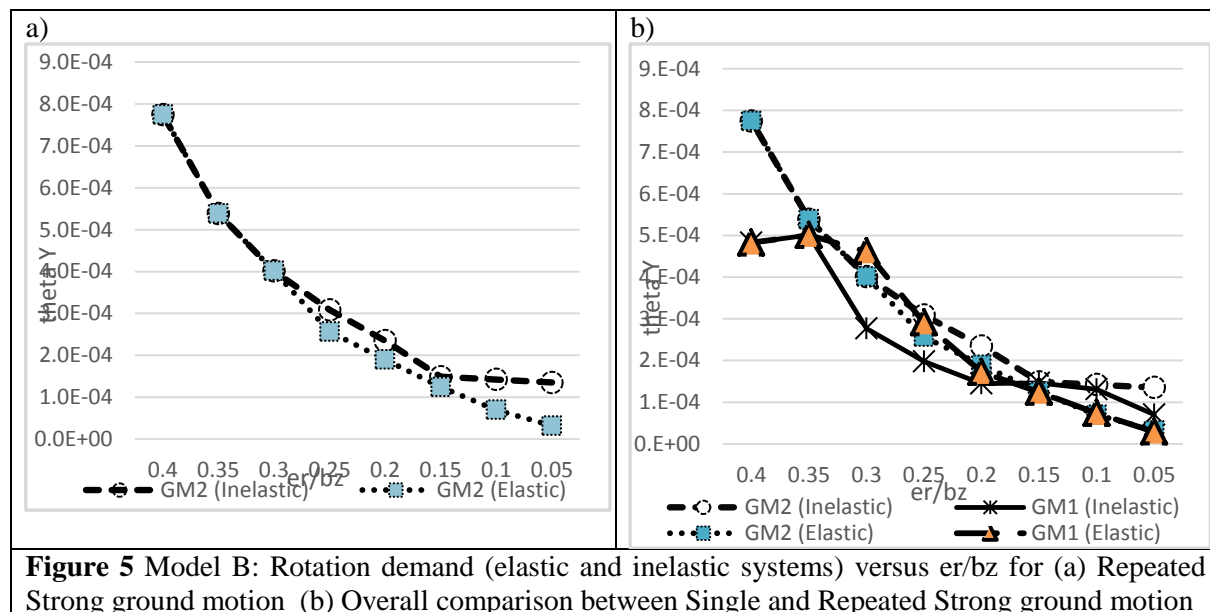


Figure 5 Model B: Rotation demand (elastic and inelastic systems) versus e_r/b_z for (a) Repeated Strong ground motion (b) Overall comparison between Single and Repeated Strong ground motion

6. Conclusion

A 3-D study on the effect of stiffness and strength eccentricities on the torsional behaviour of a building model under single and repeated, unidirectional earthquake is presented. The result for the elastic and inelastic analysis obtained based on 3-D analysis are compared with prominent past research from 2-D analysis. The results are generally agreeable and can serve as improvement to design codes, especially for lower strength eccentricities ratio i.e. $e_r/b_z \leq 0.3$ and lower stiffness eccentricities ratio i.e. $e_s/b_z > 0.20$. The study also serve as an extension for systems with extreme

strength and stiffness eccentricities since most studies study small strength eccentricities. Position Model A confirms previous works that stiffness eccentricity plays a minor role when assessing the torsional behaviour of a ductile systems. It is also found that irrespective of single or repeated ground motion, the effectiveness of CS reduces gradually until stiffness eccentricity ratio (e_s/b_z) is 0.2 from the CoM; thereafter CR becomes effective. Position Model B shows that although a structure under single strong ground motion can be sufficient for design in the elastic range as suggested by Summer [18], the findings from this work shows otherwise such that structural behaviour are more affected by repeated ground motion. That is, inelastic analysis under repeated ground motion is must be conducted to ensure that the designed structure can undertake the expected elastic/inelastic demand from repeated ground motion; especially for the lower CR ratio values.

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